ARMY RESEARCH LABORATORY

Effects of Processing Conditions on Vacuum Assisted Resin Transfer Molding Process (VARTM)

by Elias J. Rigas, Thomas J. Mulkern,
Shawn M. Walsh, and Steven P. Nguyen

ARL-TR-2480 May 2001

Approved for public release; distribution is unlimited.

20010612 008

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

ARL-TR-2480 May 2001

Effects of Processing Conditions on Vacuum Assisted Resin Transfer Molding Process (VARTM)

Elias J. Rigas, Thomas J. Mulkern, Shawn M. Walsh,
and Steven P. Nguyen,
Weapons and Materials Research Directorate, ARL

Approved for public release; distribution is unlimited.

Abstract

The continued growth of vacuum-based processes has warranted the development of both models and experimental studies designed to capture the unique aspects associated with this manufacturing technique. To that end, this report summarizes an initial set of experiments that characterize both the process and the resulting mechanical properties of components fabricated under a variety of process conditions. Specifically, resin flow studies are presented in part to demonstrate the relative influence of key parameters on the flow front developed during impregnation. The effect of the distribution medium, which is used in a commercial version of VARTM known as Seeman's Composite Resin Infusion Molding Process (SCRIMP), is explicitly characterized. In addition, the variation of part thickness is also examined, and potential mechanisms responsible for these variations are presented. A battery of mechanical tests designed to correlate the effect of various processing conditions are also presented. A major finding is that thickness variation can be significant and, to some degree, random; also, precompaction of the preform significantly influences the amount of consolidation pressure needed during impregnation. Dimensional variations due to gradients in the pressure distribution of the vacuum affect permeability (and hence resin flow), as well as dimensional tolerances in manufactured parts.

Acknowledgments

The authors wish to thank Melissa Klusewicz, David Spagnuolo, Paul Moy, John Brown, Fred Goetz, Andrew Ashton, and Doug Strand from the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, MD. We also acknowledge the work of ARL student contractors Chris Klug from the University of Maryland and Eric Fine, Scott Vandry, and Michael Poot from the University of Delaware.

INTENTIONALLY LEFT BLANK.

Contents

INTENTIONALLY LEFT BLANK.

List of Figures

INTENTIONALLY LEFT BLANK.

List of Tables

INTENTIONALLY LEFT BLANK.

1. Introduction

The benefits of vacuum assisted resin transfer molding (VARTM) are well known for certain applications (e.g., large hull structures, structural members, and transport compartments). These benefits include low volatile emissions, reduced tooling costs, and decreased cycle times associated with the process [1–2]. There is, however, the potential for the lack of part-to-part consistency, and the overall part quality may not be equal to conventional prepreg materials. Recent work has been published on the effects of fiber compaction on the quality/mechanical properties of composite materials processed with VARTM [3–10]. The lower fiber volume fraction (V_f) associated with a low-pressure molding process may not be a problem for relatively thin section, nonstructural/nonballistic applications, but for areas where thick section composites are needed, further research into process optimization must be performed. If high fiber volume, thick-section composites can be manufactured by a low cost VARTM process or by a modified VARTM process, the increased use of these materials will be seen in a variety of vehicle and structural applications.

In less than a decade, a major shift has occurred in the processing of large, relatively complex fiber-reinforced structures. This shift is centered primarily around the adoption of purely vacuum based processes and the migration to one-sided, inexpensive tooling. These processes are generally known as VARTM and include a number of patented and commercialized processes such as SCRIMP [9].

The principal advantage of the VARTM class of processes is the inherent cost-effectiveness associated with its implementation. Processing costs alone constitute between 50 and 60% of the typical end item cost; thus, there is significant incentive to continually explore new processes that can affordably provide the desired properties. A typical VARTM process is illustrated in Figure 1, where a preform is laid up onto a one-sided tool. The preform may already be stitched, or successive layers can be stacked up until the desired part thickness is achieved. Next, a series of feed tubes is placed around the structure to enable a continuous supply of resin to the part. In the case of SCRIMP [9], a patented and commercialized process, a layer of distribution medium is also inserted. In effect, the distribution medium is a highly permeable material that allows the resin to flow through a fiber preform with greater ease. A vacuum bag is subsequently fitted over all of the aforementioned materials and fixtures. It is not uncommon to use a second vacuum bag to minimize variations in compaction pressure and guard against potential vacuum leaks in the primary vacuum bag.

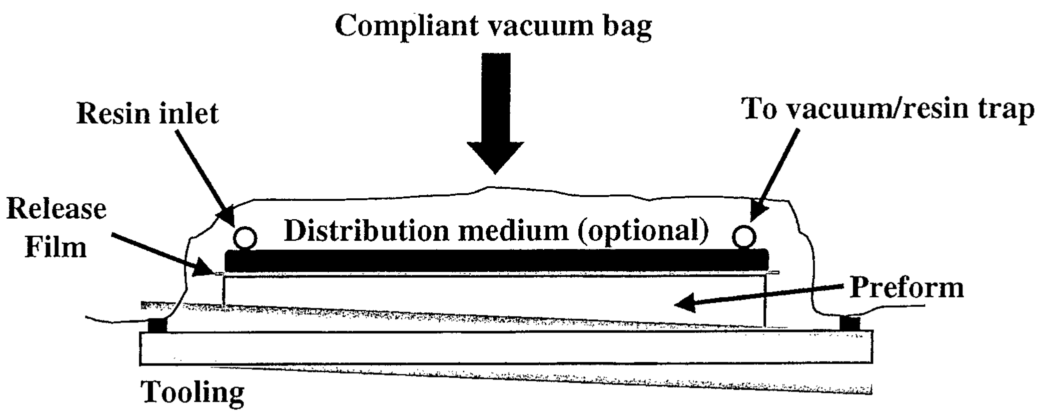

Figure 1. Typical VARTM process.

Once the process is properly configured, resin is supplied at atmospheric pressure. The pressure differential arising from the resin source at atmospheric pressure, along with the evacuated preform, stimulates resin impregnation of the fibrous preforms. Although this process appears to be quite simple, a number of disadvantages exist in the current practice of VARTM processing, and relatively little is understood about the coupled nature of the resin flow and preform consolidation [11, 12].

2. Motivation for Present Research

As the resin flow front moves away from its source, its velocity decreases in accordance with Darcy's law. Only recently have models appeared describing the unique behavior of the resin flow front in the presence of a vacuum. The industrial practice of VARTM has thus relied on trial and error to determine near optimal operating parameters and process configurations. For example, the "rule of thumb" is to place successive line sources approximately 18 in apart for a vinyl ester resin in combination with a woven glass fabric. If the spacing is much greater than this, the flow front begins to stall so significantly that the total impregnation time can be doubled. Much of the success in VARTM has been achieved through trial and error; a more rigorous and fundamental understanding of the process is required to improve the process.

3. Experimental

3.1 Materials

The reinforcement material used in this study is an Owens Corning S-2 fiberglass, 24-oz/yd^2 woven roving, 5×5 plain weave fabric. The resin used is Applied Polymeric SC-15, a rubber toughened, low viscosity epoxy. Test laminates were 20 in $\times$ 20 in $\times$ 22 plies thick; they were infused with a resin feed line across one end and a vacuum line across the other end of the part. A release film was placed on top of the preform, and then the resin distribution medium along with vacuum and resin feed lines were installed and sealed under a vacuum bag.

3.2 Methods

Several approaches were taken to determine how a fiber preform compresses and fills. To determine theoretical maximum fiber nesting, the mechanical compressibility of dry and wet fiber preforms was conducted on an Instron load frame. Mechanical test specimens using different VARTM processing techniques, as well as one set cured in a mechanical press, were made to determine mechanical variations among different techniques. Variations in the infusion and bagging methods were investigated, as well as preform infusion time with and without a resin distribution medium. All infused parts were fabricated on a glass tabletop, as shown in Figure 2, where both top and bottom infusion times could be determined.

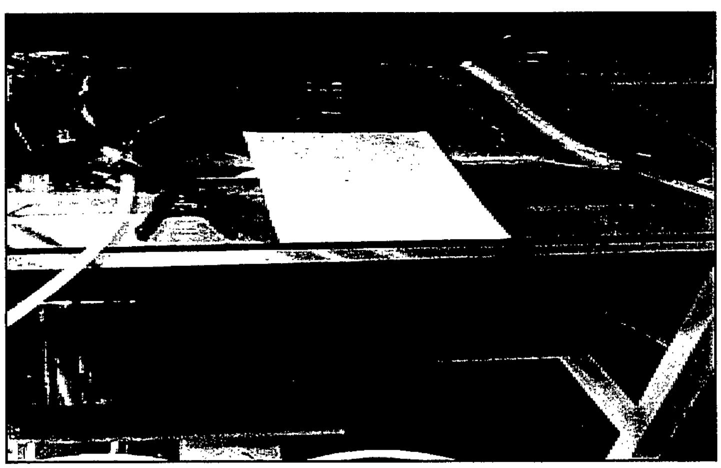

Figure 2. Infusion on glass tabletop with mirror underneath to observe and record flow on bottom of preform.

3.3 Mechanical Compressibility of Fiber Preform

The fiber volume fractions (V_f) of glass preforms were estimated using an Instron 1145 mechanical load frame operated under load control. The crosshead displacement was determined using a linear variable displacement transducer. Load and displacement data were collected as a function of time. The crosshead displacement of the load frame was used to determine the thickness of the fiber pack, and it enabled the calculation of theoretical fiber volume fraction. Both dry- and resin-infused preforms were compressed under static and dynamic loads to determine the potential V_f of the composite plates manufactured under different processing conditions. In each test, nine plies of fiberglass fabric were subjected to different loading conditions. Nine ply specimens were fabricated for all the mechanical tests using the same processing conditions as the 22-ply preforms in the flow studies.

A series of tests were conducted to measure the V_f of a dry- and resin-infused composite preform under dynamic and static loads. The resin-infused composite preforms were cured between the platens of the mechanical load frame after cyclic loading to compare to parts made in a mechanical compression press.

3.4 Physical/Mechanical Properties

The physical and mechanical properties of the composite materials were determined according to ASTM standards. The fiber volume fraction of the composites was determined through ASTM D4963. The apparent interlaminar shear strength was determined by the ASTM D2344 short beam shear method, while the flexural modulus and flexural strength were determined by ASTM D790. The tensile modulus and tensile strength were determined by ASTM D638, and the interlaminar shear response was determined by ASTM D3518 in $\pm 45°$ tension.

3.5 Resin Infusion Experiments

Variations in infusion times were monitored and recorded while infusing 22 plies of S2 glass, 24 oz/yd^2, 5×5 plain weave fabric. Relative to the preform, the height of the resin feed source was varied to determine the effects of gravity on total fill time. One set of preforms was infused with the resin feed source placed approximately 3 ft below the preform surface. A second set was infused with the resin feed source at the same height as the preform. A third set of panels was infused with the resin feed source placed at the same height as the preform, but a semi-rigid transparent thermoplastic sheet was added between the distribution medium and the vacuum bag. This was done to determine whether the rigid thermoplastic sheet would have an effect similar to a compression press with a rigid surface on both sides of the preform. Five panels were infused using each

method, and the averages are reported. All parts were infused using a single vacuum bag while incorporating a 50% shade distribution medium on top of the preform (shade refers to the approximate amount of light the distribution medium blocks out). After infusion, parts were cured using either single or double bagging techniques to evaluate how this affects the cured thickness.

Another set of experiments was conducted to provide both quantitative and qualitative assessments of the effect of using a distribution medium in the VARTM process. Using a highly porous distribution medium sandwiched between the preform and the vacuum bag is patent protected by Seeman [9]. A flow experiment was devised to reveal the relative effect of including a distribution medium. The general features of the experiment are shown in Figure 3.

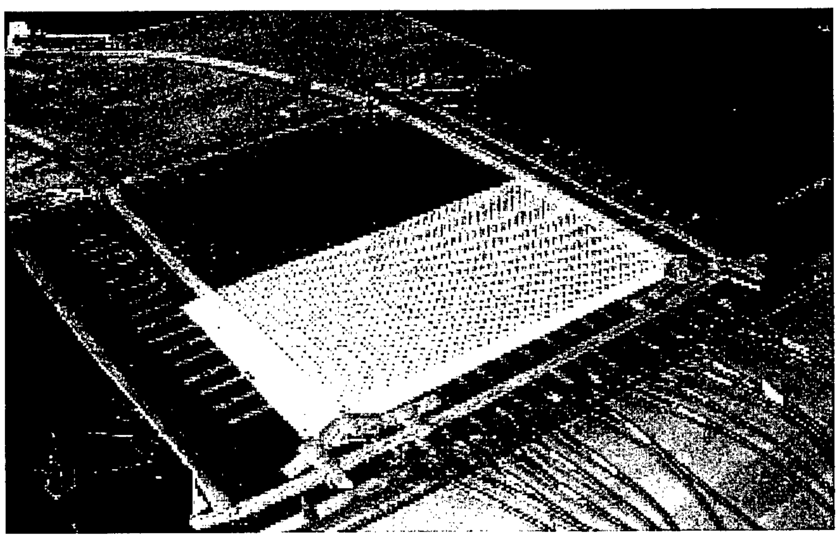

Figure 3. Laminate with distribution medium on left half.

As Figure 3 shows, a layer of distribution medium was applied to only one half of a six-ply woven S-2 glass preform. A uniform line source has been orthogonally located on one end; similarly, a vacuum outlet is located at the other. A layer of SMARTweave [13] was installed to capture the location of the flow front on the tool side; this is explicitly shown in Figure 4. In this particular apparatus, the tool side was 1/2-in-thick plate glass. Glass was selected not only to provide direct visualization of the flow front, but also to validate the utility of SMARTweave as a practical in-situ method for locating flow movement and rate. For this experiment, a resin simulant consisting of corn syrup and water was used; the viscosity of the simulant was adjusted to mimic that of a typical epoxy. The instantaneous location of the flow front was obtained by tracing the contours at 30-s intervals on the top and bottom layers of the glass, as shown in Figure 5.

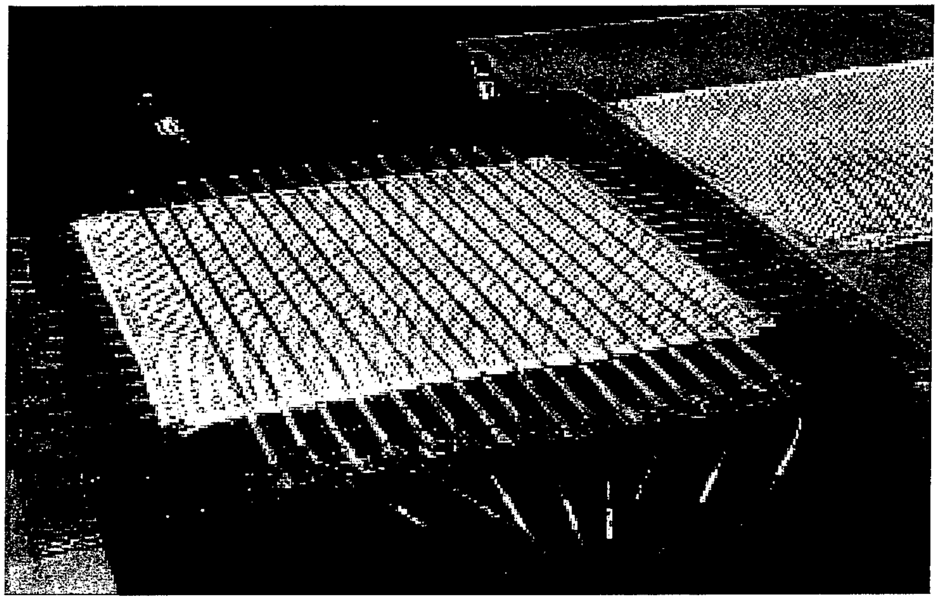

Figure 4. Installation of SMARTweave adjacent to tool (glass) surface.

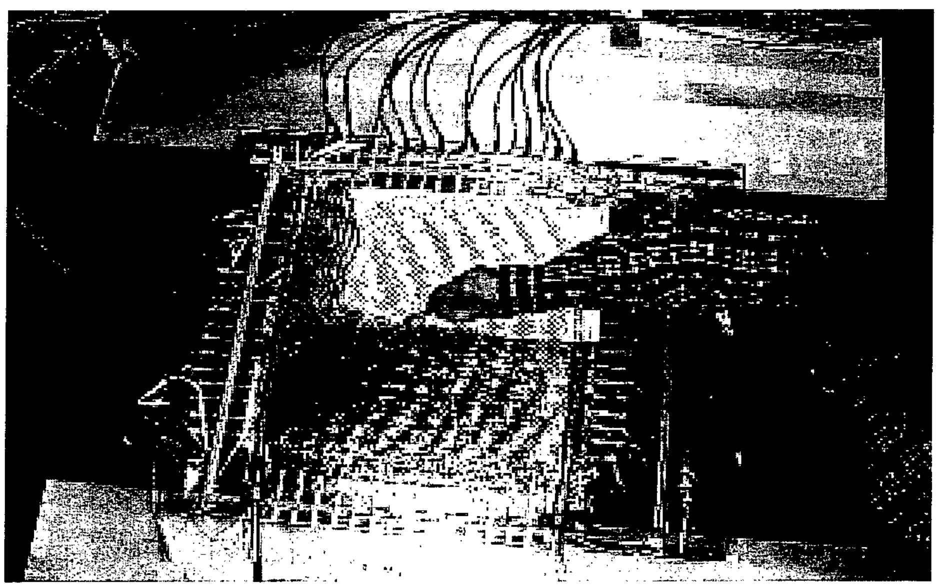

Figure 5. Manual tracing of flow fronts during impregnation.

4. Results and Discussion

4.1 Discussion of Flow Results

The effect of the distribution medium in infusing a preform was dramatic, as anticipated. The flow front traversed the distance from the line source to the vacuum line in less than 4 min on the side of the laminate containing the distribution medium. It took over 2 hr for the flow front to traverse the same distance on the side without the distribution medium. However, there are key points and differences to be noted in comparing these results. First, these time comparisons were made on the top layer. It took over 30 min for the flow to traverse the same distance on the bottom surface (beneath the half with the distribution medium). That is, there was a significant transfer flow gradient through the thickness of the part. In contrast, there was virtually no gradient in the side without the distribution medium (i.e., the flow front was near plug flow, proceeding at the same rate throughout the thickness of the laminate). In addition, the rapid arrival of resin at the vacuum on the side with the distribution medium appears to have resulted in a significant drop off in vacuum pressure, thus causing the flow to stall significantly on the side without the distribution medium. The effect of liquid prematurely reaching the vacuum was studied previously [14]. The location and nature of the vacuum can play a very significant role in flow front development during impregnation.

The flow front behavior on the tool surface of the side containing the distribution medium revealed other effects, as indicated by the contours shown in Figure 6. First, even though the flow progresses more rapidly on the surface below the distribution medium, the flow front itself was notably irregular. The flow appeared to stall and then "leap" ahead, as indicated by the peaks of the contour curves. This phenomenon occurred at least three times during the impregnation. This effect has been informally reported from various users of VARTM processing. Figure 6 conclusively reveals the behavior of the flow front on the otherwise inaccessible tool side. Given that a glass tool is not practical in an actual processing scenario, SMARTweave [13] is thus presented as a viable means for monitoring flow.

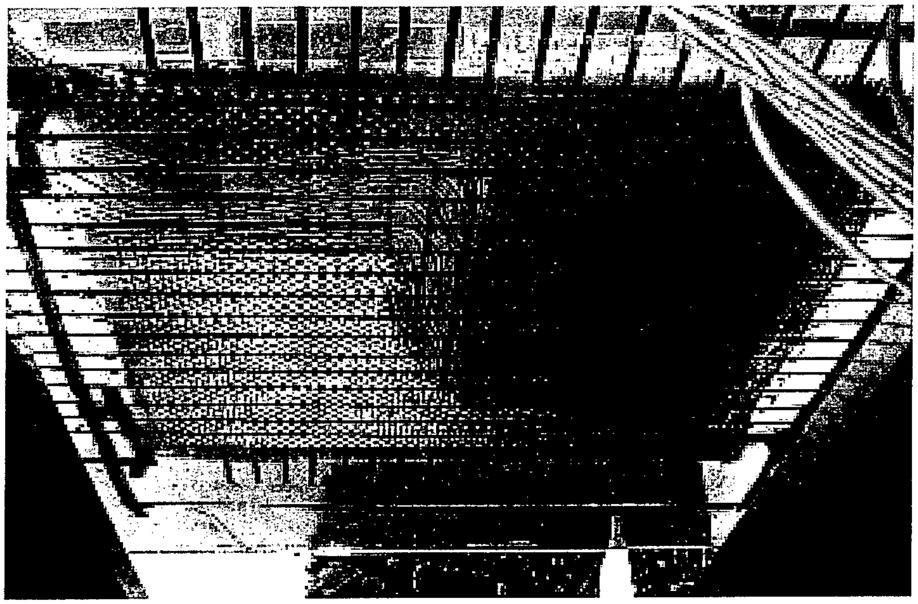

Figure 6. Bottom view of flow front contours on tool (glass) surface.

4.2 Discussion of Resin Infusion Results

Another set of experiments was conducted using a 22-ply preform with a distribution medium across the entire top layer. A rubber-toughened epoxy was used for these experiments. Average resin flow front times in seconds, across the surface of the part, for three different infusion methods are studied. The first method involved feeding the part with the resin feed source placed on the floor approximately 3 ft below the preform surface. The second method had the resin feed source elevated to the same height as the preform. The third method had the resin feed source placed at the same height as the preform, but with a semi-rigid transparent thermoplastic sheet added over the distribution medium but under the vacuum bag. All preforms were 20 in $\times$ 20 in with the distribution medium 18 in $\times$ 18 in. Figure 7 shows the average infusion times across the top layer for each method as a function of distance traveled. Figure 8 shows the corresponding average infusion times for the flow fronts across the bottom layer for each method.

As a function of distance from the vacuum source, variations in final part thickness were measured after the parts were fully cured. The elevated and elevated with plexiglas flow experiments were cured with a double bag after they were fully infused. This was done to gauge if a second vacuum bag affected part thickness. The final cured thickness of a part decreases as the vacuum source is approached, as shown in Figure 9. It should be noted that these averages are taken from parts manufactured using a line feed source on one end and a line vacuum source on the other end.

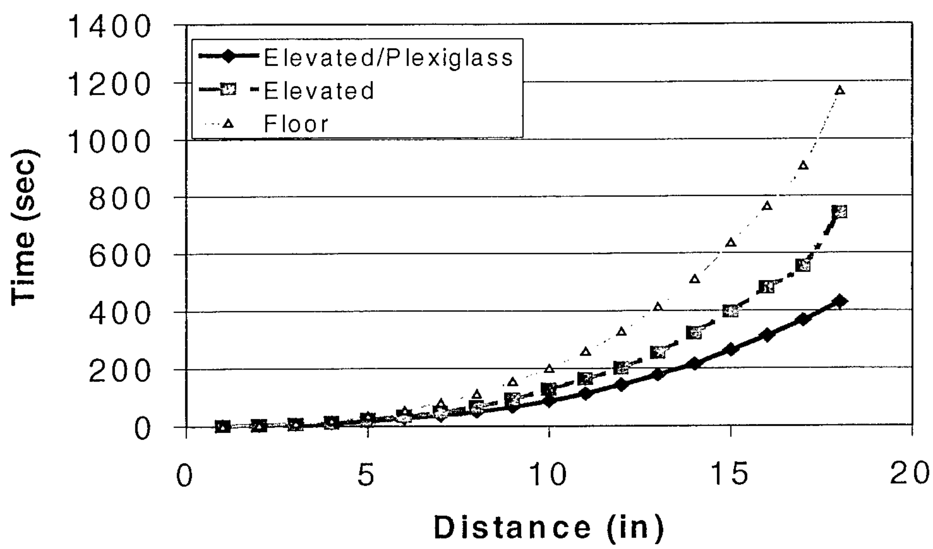

Figure 7. Infusion time across top of preform surface.

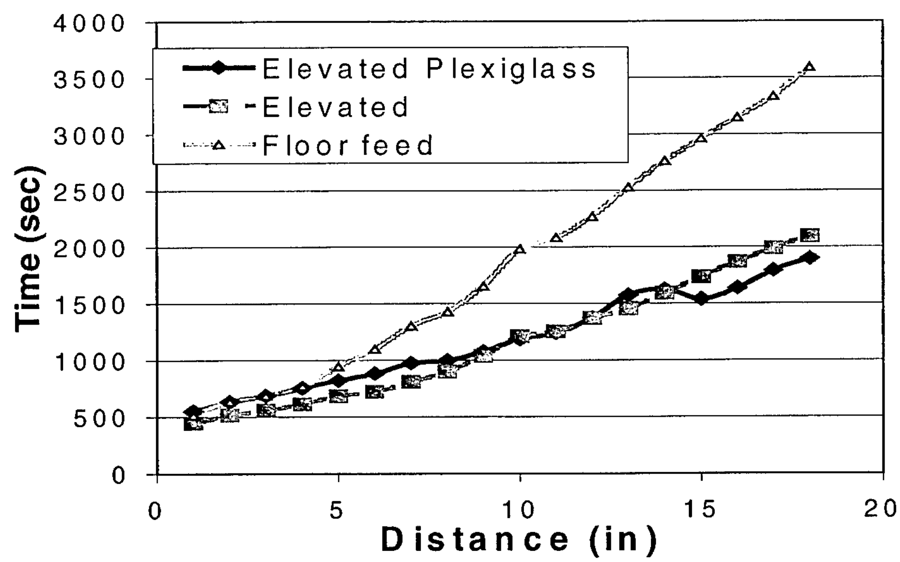

Figure 8. Infusion time across bottom of preform surface.

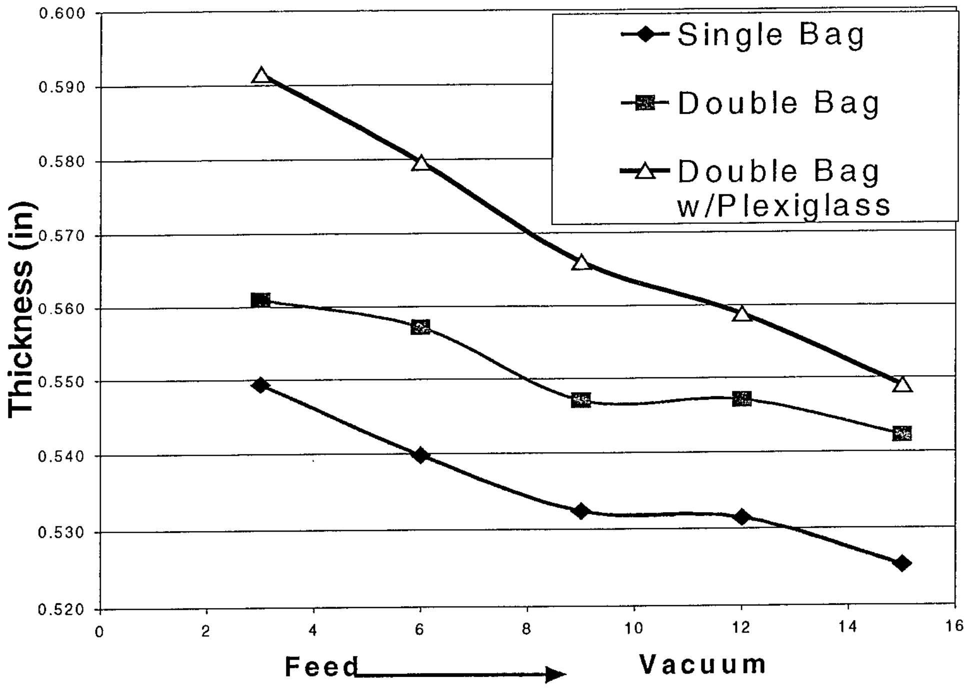

Figure 9. Cured part thickness vs. distance relative to vacuum source.

As a consequence of part to part thickness variations, there is a corresponding variation in the fiber volume fraction of the final part. As the distance from the vacuum source increases, the fiber volume fraction of the laminates decreases; this phenomenon is apparent in Figure 10.

4.3 Material Properties/Compressibility

Several experiments were also performed on the compressibility of the fiberglass preforms to determine the effects of pressure on the V_f. Dry fiberglass preforms were loaded from 0 to 6 atm in the first series of tests. Figures 11 and 12 illustrate the effect of pressure on 43 and 9 plies of glass fabric, respectively. The 43-ply sample has the lowest initial V_f of 50%, and the 9-ply preform has a higher initial V_f of 55%. Since perfect fiber bundle nesting does not occur in practice, the thicker the preform the higher the potential for part to part variations due to an increase of free volume in every additional layer of reinforcement. By mechanically loading and unloading the preform, a maximum V_f may be attained prior to applying vacuum pressure for resin infusion. This, however, may adversely affect the resin permeability.

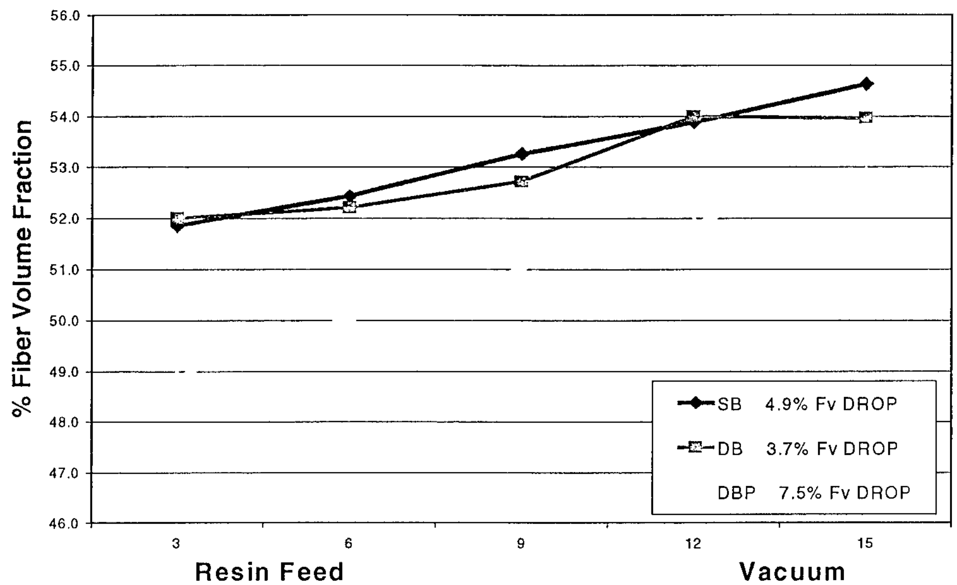

Figure 10. Graph of fiber volume fraction change vs. distance relative to vacuum.

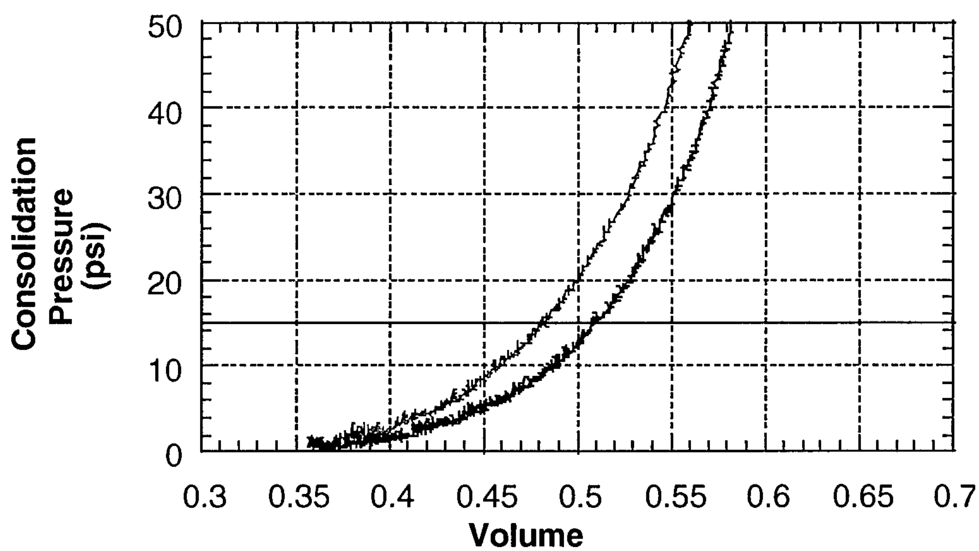

Figure 11. Compressibility curves for 43 plies of fiberglass fabric loaded twice from 0 to 90 psi (full scale not shown).

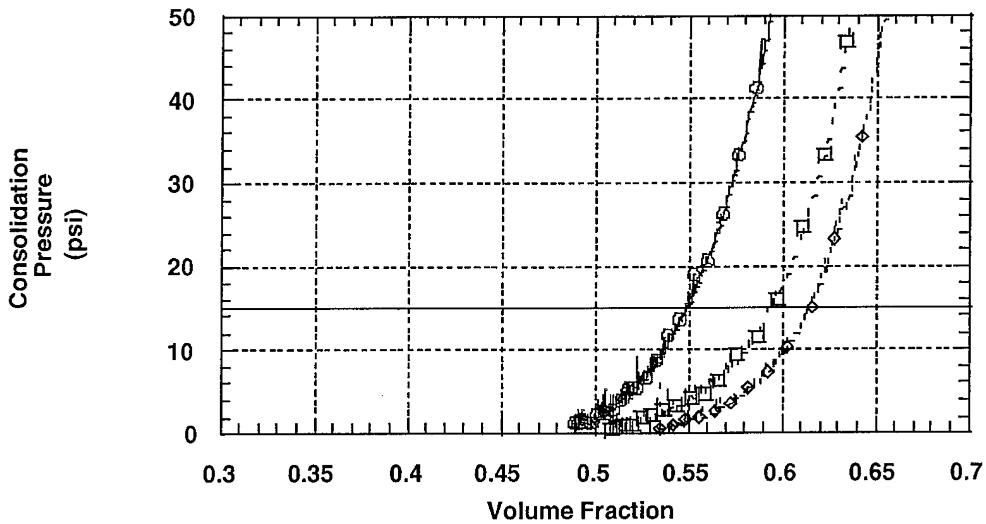

Figure 12. Compressibility curves for nine plies of fiberglass fabric loaded three times from 0 to 90 psi (full scale not shown).

Another series of tests was performed to simulate the effects of low vacuum pressure on the compressibility of a fiberglass preform. A load was applied to the dry laminate and held for approximately 30 min, as shown in Figure 13. This load is equal to 0.33 atm of pressure and would simulate consolidation and infusion under poor vacuum conditions or a broken vacuum bag scenario. The maximum V_f achieved under these conditions was approximately 46%.

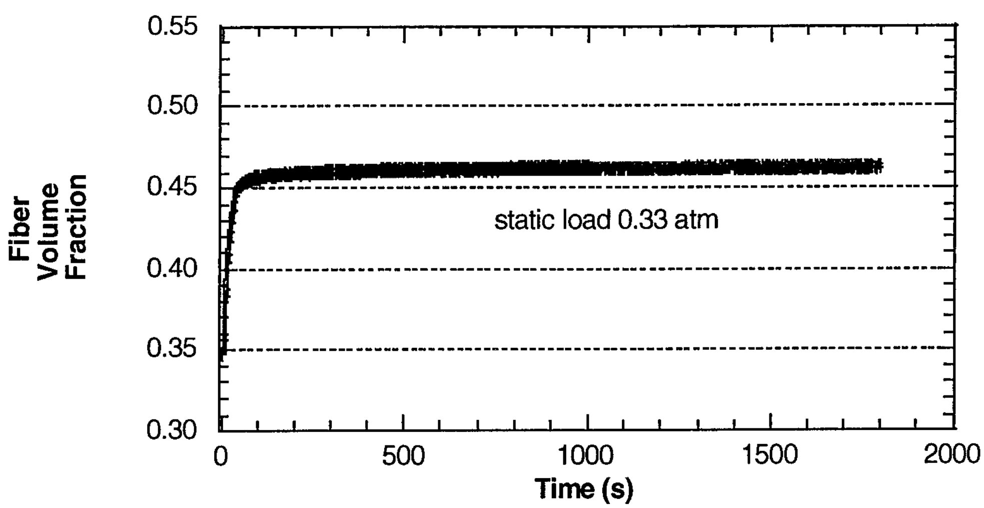

Figure 13. Compressibility curves for nine plies of fiberglass fabric loaded from 0 atm to 0.33 atm (0–5 psi).

In Figure 14, a load was applied to a dry laminate and held for approximately 30 min. This is equal to 1 atm of pressure and would simulate ideal vacuum conditions. The maximum V_f achieved was approximately 49%. The preform was then unloaded and reloaded to 1 atm, where the predicted V_f reached a value of 53%.

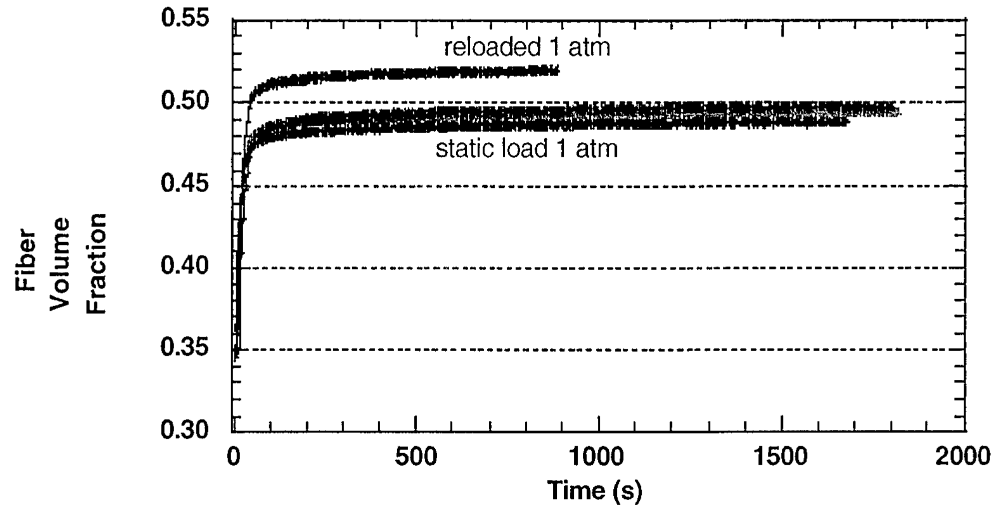

Figure 14. Compressibility curves for nine plies of fiberglass fabric loaded from 0 atm to 1 atm (0–15 psi). Top curve loaded twice from 0 atm to 1 atm (0–15 psi), which resulted in a higher fiber volume fraction.

Static and dynamic loads were applied to fiberglass preforms to evaluate the effect of loading on V_f. In Figure 15, a static load of 1-atm pressure was applied to the preform and held. A dynamic load, which cycled from 0.33 atm to 1 atm, was also applied to a nine-ply preform. This simulates the process of applying and releasing vacuum pressure during the bagging portion of a typical VARTM layup.

The data shows a small increase in the V_f of the dynamically loaded preform. This may account for some final part to part variations observed after processing since the vacuum pressure and how it has been applied may not always be the same from one VARTM run to the next. It may also be a useful parameter/design tool in producing higher V_f parts with reproducible properties. Although there is some elastic recovery, or spring back, of the fiberglass preform associated with reducing the pressure, it is not fully reversible within the given time frame. When the vacuum pressure is reduced from 1 to 0.33 atm in this experiment, the V_f is higher than the maximum V_f attained under statically loading the preform to 0.33 atm.

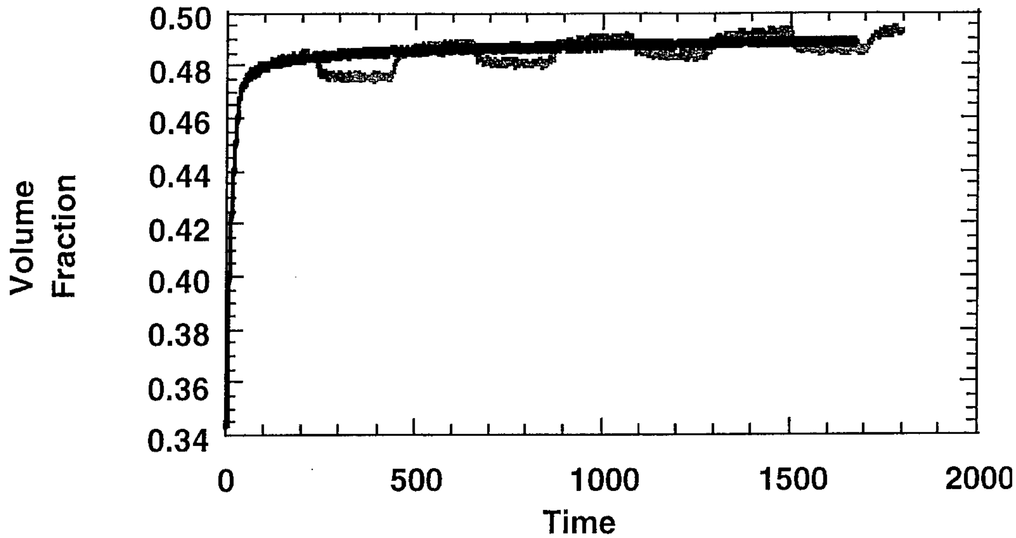

Figure 15. Comparison of static (15 psi) and dynamic (5–15 psi) loading on a fiberglass preform.

An additional dynamic loading experiment was performed to determine the lubrication effect of resin on the compressibility of a fiberglass preform. A nine-ply preform was infused with resin and loaded dynamically from 0.33 to 1 atm, as shown in Figure 16. This resulted in a theoretical V_f of 58% based on the cross-head displacement, which was a 16% increase over the dry fabric loaded in the same manner. This clearly illustrates the lubrication effect of the resin during any composites processing scheme.

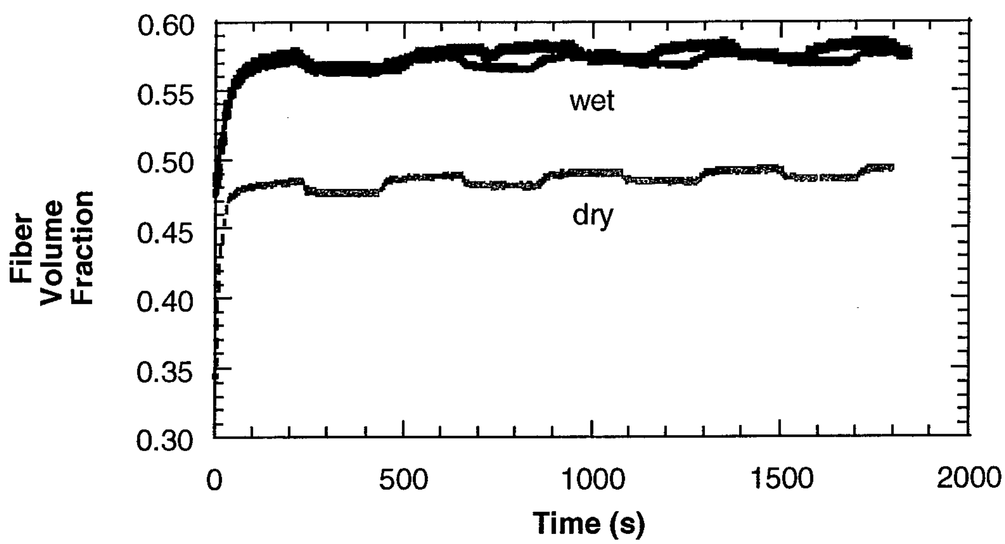

Figure 16. Comparison of wet and dry fiberglass preforms under dynamic loading (5–15 psi).

4.4 Physical and Mechanical Properties

The theoretical V_f values from the compressibility studies are compiled in Table 1. Not only can the V_f be changed by increasing the consolidation pressure, but also by applying a cyclic load or lubricating the fibers.

Table 1. Predicted fiber volume fractions of wet and dry fiberglass preforms compressed in an Instron mechanical test frame.

Wet/Dry	No. of Plies	Pressure (atm)	No. of Cycles	V_f at 1 atm
dry	43	0–6	2	51
dry	9	0–6	3	62
dry	9	0.33	1	47
dry	9	1	1	50
dry	9	1	2	52
dry	9	0.33–1	6	50
wet	9	0.33–1	6	59

The actual fiber volume fractions (V_f) of the composite laminates produced under different conditions are listed in Table 2. However, all of the values do not correspond to the predicted theoretical values based on the Instron data. The V_f value of 60.14% attained in the mechanical press and the 60.65% attained from the cured Instron samples correlate with the 59% V_f predicted with the wet preform compressed in the Instron. The V_f values calculated from the single- and double-bag VARTM do not correspond to the predicted values of preforms loaded under 1 atm of pressure. This may be attributed to poor vacuum pressure during processing. Or, it may be due to the inability of the process to remove excess resin after complete wet out, resulting in a lower V_f.

Table 2. Fiber volume fractions of composite parts processed under different conditions.

Resin Infusion Method	No. of Plies	Fiber Volume Fraction (%)
Single-Bag VARTM	8	51.13
Double-Bag VARTM	8	49.93
Mechanical Press VARTM	8	60.14
Instron Samples	9	60.65

The mechanical properties are presented in Table 3; they have been normalized to a V_f of 60%. The properties are consistent from one process to another as well as published manufacturer data [15]. The only obvious difference between the press and the VARTM processes is the variation in thickness and the V_f. The laminates processed between the platens of a mechanical press or in the Instron had a lower part thickness and higher V_f when compared to the VARTM laminates.

Table 3. Mechanical properties of composite materials processed under different conditions.

Processing Method	ASTM Test Method	Mechanical Press	Single Bag VARTM
Fiber Volume Fraction	D 4693	60.14	51.13
Apparent Shear Strength (ksi) CV	D 2344	6.06 5.52	5.97 3.50
Norm Flex Mod (Msi) CV	D 790	4.7 0.8	4.4 0.7
Norm Flexural Strength (ksi) CV	D 790	78.6 4.04	83.3 5.52
Norm $G_{12chord}$ (Msi) CV	D 3518	2.02 4.22	1.80 2.58
Norm Shear Stress (ksi) at 5% Strain CV	D 3518	8.03 8.50	8.27 3.80

5. Conclusions

It has been quantifiably demonstrated that the elevation of the resin feed source relative to the part can significantly affect the time it takes to infuse a part using VARTM. The presence of the resin distribution medium's effect on the infusion time has been examined quantitatively and qualitatively. It has also been shown that vacuum and resin source location affect resin infusion time and final part quality. Parts manufactured with either a single or double bag have a tendency to be thinner as the part approaches the location of the vacuum source.

The amount of consolidation pressure, as well as the method of applying pressure, has an effect on the final part geometry and V_f of a thick-section composite laminate. If thinner laminates with higher V_f are required for a given application, novel techniques of applying pressure and removing excess resin may be used to attain desired properties.

The goal is to remove as much of the labor and waste from the VARTM process as possible and provide a flexible, effective means for ensuring that the process produces the desired mechanical properties. To that end, using external visualization techniques coupled with embedded sensors provides a wealth of information hitherto unavailable from which to produce a closed loop process control system for VARTM manufacturing. The control system can be continuously expanded to include some of the effects studied in this report, including the adjustment of resin feed source, uniformity of consolidation, and the effect of locating and actuating both resin and vacuum sources.

INTENTIONALLY LEFT BLANK.

6. References

1. Williams, C., J. Summerscales, and S. Grove. "Resin Infusion Under Flexible Tooling (RIFT): A Review." *Composites Part A*, vol. 27A, pp. 517–524, 1996.
2. Steenkamer, D. A., V. M. Karbhari, D. J. Wilkins, and D. S. Kukich. "An Overview of the Resin Transfer Molding Process." CCM Report 94-02, University of Delaware, Newark, DE, 1994.
3. Abraham, D., S. Mathews, and R. McIlhagger. "A Comparison of Physical Properties of Glass Fibre Epoxy Composites Produced by Wet Lay-Up with Autoclave Consolidation and Resin Transfer Moulding." *Composites Part A*, vol. 29A, pp. 795–801, 1998.
4. Falzon, P. J., I. Herszenberg, and V. M. Karbhart. "Effects of Compaction on the Stiffness and Strength of Plain Weave Fabric RTM Composites." *Journal of Composite Materials*, vol. 30, no. 11, p. 1210, 1996.
5. Breiling, K. B., and D. O. Adams. "Effects of Layer Nesting on Compression-Loaded 2-D Woven Textile Composites." *Journal of Composite Materials*, vol. 30, no. 15, pp. 1710-1729, 1996.
6. Pearce, N., and J. Summerscales. "Compressibility of a Reinforcement Fabric." *Composites Manufacturing*, vol. 6, pp. 15–21, 1995.
7. Toll, S. "Packing Mechanics of Fiber Reinforcements." *Polymer Engineering and Science* [H. W. Wilson - AST], vol. 38, no. 8, pp.1337–1350, August 1998.
8. Pearce, N., F. Guild, and J. Summerscales. "An Investigation Into the Effects of Fabric Architecture on the Processing and Properties of Fibre Reinforced Composites Produced by Resin Transfer Moulding." *Composites Part A*, vol. 29A, pp. 19–27, 1998.
9. Seeman, W. H. "Plastic Transfer Molding Techniques for Production of Fiber Reinforced Plastic Structures." U.S. Patent No. 4,902,215, February 1990.
10. Saunders, R. A., C. Lekakou, and M. G. Bader. "Compression in the Processing of Polymer Composites Parts 1 and 2." *Composite Science and Technology*, vol. 59, 1999.
11. Luo, Y., and I. Verpoest. "Compressibility and Relaxation of a New Sandwich Textile Preform for Liquid Composite Moulding." *Polymer Composites*, vol. 20, no. 2, April 1999.

12. Sun, X., S. Li, and J. Lee. "Mold Filling Analysis in Vacuum Assisted Resin Transfer Molding. Part I: SCRIMP Based on a High-Permeable Medium." *Polymer Composites*, vol. 19, no. 6, December 1998.

13. Walsh, S. M. "In-Situ Sensor Method and Device." U.S. Patent No. 5,210,499, 1991.

14. Walsh, S. M., and R. V. Mohan. "Study of Staggered Flow Fronts With Applications to Sensor-Based Control." Proceedings of SPE ANTEC, 2681-2685, New York, NY, May 1999.

15. Owens Corning S-2 Glass® Product Information. Pub. No. 1-PL-14973-G, 1995.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDR&E(R) DR R J TREW 3800 DEFENSE PENTAGON WASHINGTON DC 20301-3800
1	COMMANDING GENERAL US ARMY MATERIEL CMD AMCRDA TF 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
1	DARPA SPECIAL PROJECTS OFFICE J CARLINI 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	US MILITARY ACADEMY MATH SCI CTR EXCELLENCE MADN MATH MAJ HUBER THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D DR D SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AI R 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AP 2800 POWDER MILL RD ADELPHI MD 20783-1197
	<u>ABERDEEN PROVING GROUND</u>
2	DIR USARL AMSRL CI LP (BLDG 305)

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TP 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR DA OASARDA SARD SO 103 ARMY PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASST SECY FOR R&T SARD TT THE PENTAGON RM 3EA79 WASHINGTON DC 20301-7100
1	COMMANDER US ARMY MATERIEL CMD AMXMI INT 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
4	COMMANDER US ARMY ARDEC AMSTA AR CC G PAYNE J GEHBAUER C BAULIEU H OPAT PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
2	COMMANDER US ARMY ARDEC AMSTA AR AE WW E BAKER J PEARSON PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR TD C SPINELLI PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSE PICATINNY ARSENAL NJ 07806-5000
6	COMMANDER US ARMY ARDEC AMSTA AR CCH A W ANDREWS S MUSALLI R CARR M LUCIANO E LOGSDEN T LOUZEIRO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSF T C LIVECCHIA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA ASF PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T C C PATEL PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR M D DEMELLA PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR FSA A WARNASH B MACHAK M CHIEFA PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR FSP G M SCHIKSNIS D CARLUCCI PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSP A P KISATSKY PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR CCH C H CHANIN S CHICO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T D RIGOGLIOSO PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY ARDEC AMSTA AR WET T SACHAR BLDG 172 PICATINNY ARSENAL NJ 07806-5000
9	COMMANDER US ARMY ARDEC AMSTA AR CCH B P DONADIA F DONLON P VALENTI C KNUTSON G EUSTICE S PATEL G WAGNECZ R SAYER F CHANG PICATINNY ARSENAL NJ 07806-5000
6	COMMANDER US ARMY ARDEC AMSTA AR CCL F PUZYCKI R MCHUGH D CONWAY E JAROSZEWSKI R SCHLENNER M CLUNE PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR SRE D YEE PICATINNY ARSENAL NJ 07806-5000
6	PM SADARM SFAE GCSS SD COL B ELLIS M DEVINE R KOWALSKI W DEMASSI J PRITCHARD S HROWNAK PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	US ARMY ARDEC INTELLIGENCE SPECIALIST AMSTA AR WEL F M GUERRIERE PICATINNY ARSENAL NJ 07806-5000
2	PEO FIELD ARTILLERY SYS SFAE FAS PM H GOLDMAN T MCWILLIAMS PICATINNY ARSENAL NJ 07806-5000
11	PM TMAS SFAE GSSC TMA R MORRIS C KIMKER D GUZOWICZ E KOPACZ R ROESER R DARCY R MCDANOLDS L D ULISSE C ROLLER J MCGREEN B PATTER PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR WEA J BRESCIA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC PRODUCTION BASE MODERN ACTY AMSMC PBM K PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY TACOM PM ABRAMS SFAE ASM AB 6501 ELEVEN MILE RD WARREN MI 48397-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY TACOM AMSTA SF WARREN MI 48397-5000
3	COMMANDER US ARMY TACOM PM TACTICAL VEHICLES SFAE TVL SFAE TVM SFAE TVH 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM BFVS SFAE ASM BV 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM AFAS SFAE ASM AF 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM RDT&E SFAE GCSS W AB J GODELL 6501 ELEVEN MILE RD WARREN MI 48397-5000
2	COMMANDER US ARMY TACOM PM SURV SYS SFAE ASM SS T DEAN SFAE GCSS W GSI M D COCHRAN 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	US ARMY CERL R LAMPO 2902 NEWMARK DR CHAMPAIGN IL 61822

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY TACOM PM SURVIVABLE SYSTEMS SFAE GCSS W GSI H M RYZYI 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM BFV SFAE GCSS W BV S DAVIS 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM LIGHT TACTICAL VHCLS AMSTA TR S A J MILLS MS 209 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM CHIEF ABRAMS TESTING SFAE GCSS W AB QT T KRASKIEWICZ 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER WATERVLIET ARSENAL SMCWV QAE Q B VANINA BLDG 44 WATERVLIET NY 12189-4050
1	COMMANDER WATERVLIET ARSENAL SMCWV SPM T MCCLOSKEY BLDG 253 WATERVLIET NY 12189-4050
2	TSM ABRAMS ATZK TS S JABURG W MEINSHAUSEN FT KNOX KY 40121

NO. OF COPIES	ORGANIZATION
15	COMMANDER US ARMY TACOM AMSTA TR R J CHAPIN R MCCLELLAND D THOMAS J BENNETT D HANSEN AMSTA JSK S GOODMAN J FLORENCE K IYER D TEMPLETON A SCHUMACHER AMSTA TR D D OSTBERG L HINOJOSA B RAJU AMSTA CS SF H HUTCHINSON F SCHWARZ WARREN MI 48397-5000
3	ARMOR SCHOOL ATZK TD R BAUEN J BERG A POMEY FT KNOX KY 40121
11	BENET LABORATORIES AMSTA AR CCB R FISCELLA G D ANDREA E KATHE M SCAVULO G SPENCER P WHEELER K MINER J VASILAKIS G FRIAR R HASENBEIN AMSTA CCB R S SOPOK WATERVLIET NY 12189-4050
2	HQ IOC TANK AMMUNITION TEAM AMSIO SMT R CRAWFORD W HARRIS ROCK ISLAND IL 61299-6000

NO. OF COPIES	ORGANIZATION
2	DAVID TAYLOR RESEARCH CTR R ROCKWELL W PHYILLAIER BETHESDA MD 20054-5000
2	COMMANDER US ARMY AMCOM AVIATION APPLIED TECH DIR J SCHUCK FT EUSTIS VA 23604-5577
1	DIRECTOR US ARMY AMCOM SFAE AV RAM TV D CALDWELL BLDG 5300 REDSTONE ARSENAL AL 35898
2	US ARMY CORPS OF ENGINEERS CERD C T LIU CEW ET T TAN 20 MASS AVE NW WASHINGTON DC 20314
1	US ARMY COLD REGIONS RSCH & ENGRNG LAB P DUTTA 72 LYME RD HANOVER NH 03755
1	SYSTEM MANAGER ABRAMS ATZK TS LTC J H NUNN BLDG 1002 RM 110 FT KNOX KY 40121
1	USA SBCCOM PM SOLDIER SPT AMSSB PM RSS A J CONNORS KANSAS ST NATICK MA 01760-5057
3	BALLISTICS TEAM AMSSB RIP PHIL CUNNIFF JOHN SONG WALTER ZUKAS KANSAS ST NATICK MA 01760-5057

NO. OF COPIES	ORGANIZATION
2	MATERIAL SCIENCE TEAM AMSSB RSS JEAN HERBERT MICHAEL SENNETT KANSAS ST NATICK MA 01760-5057
2	OFC OF NAVAL RESEARCH D SIEGEL CODE 351 J KELLY 800 N QUINCY ST ARLINGTON VA 22217-5660
1	NAVAL SURFACE WARFARE CTR DAHLGREN DIV CODE G06 DAHLGREN VA 22448
1	NAVAL SURFACE WARFARE CTR TECH LIBRARY CODE 323 17320 DAHLGREN RD DAHLGREN VA 22448
1	NAVAL SURFACE WARFARE CTR CRANE DIVISION M JOHNSON CODE 20H4 LOUISVILLE KY 40214-5245
8	DIRECTOR US ARMY NATIONAL GROUND INTELLIGENCE CTR D LEITER M HOLTUS M WOLFE S MINGLEDORF J GASTON W GSTATTENBAUER R WARNER J CRIDER 220 SEVENTH ST NE CHARLOTTESVILLE VA 22091
3	NAVAL RESEARCH LAB I WOLOCK CODE 6383 R BADALIANCE CODE 6304 L GAUSE WASHINGTON DC 20375
2	NAVAL SURFACE WARFARE CTR U SORATHIA C WILLIAMS CD 6551 9500 MACARTHUR BLVD WEST BETHESDA MD 20817

NO. OF COPIES	ORGANIZATION
6	US ARMY SBCCOM SOLDIER SYSTEMS CENTER BALLISTICS TEAM J WARD MARINE CORPS TEAM J MACKIEWICZ BUS AREA ADVOCACY TEAM W HASKELL SSCNC WST W NYKVIST T MERRILL S BEAUDOIN KANSAS ST NATICK MA 01760-5019
9	US ARMY RESEARCH OFC A CROWSON J CHANDRA H EVERETT J PRATER R SINGLETON G ANDERSON D STEPP D KISEROW J CHANG PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
8	NAVAL SURFACE WARFARE CTR J FRANCIS CODE G30 D WILSON CODE G32 R D COOPER CODE G32 J FRAYSSE CODE G33 E ROWE CODE G33 T DURAN CODE G33 L DE SIMONE CODE G33 R HUBBARD CODE G33 DAHLGREN VA 22448
2	COMMANDER NAVAL SURFACE WARFARE CTR CARDEROCK DIVISION R PETERSON CODE 2020 M CRITCHFIELD CODE 1730 BETHESDA MD 20084
1	NAVAL SEA SYSTEMS CMD D LIESE 2531 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5160

NO. OF COPIES	ORGANIZATION
1	NAVAL SURFACE WARFARE CTR M LACY CODE B02 17320 DAHLGREN RD DAHLGREN VA 22448
2	NAVAL SURFACE WARFARE CTR CARDEROCK DIVISION R CRANE CODE 2802 C WILLIAMS CODE 6553 3A LEGGETT CIR BETHESDA MD 20054-5000
1	EXPEDITIONARY WARFARE DIV N85 F SHOUP 2000 NAVY PENTAGON WASHINGTON DC 20350-2000
1	AFRL MLBC 2941 P ST RM 136 WRIGHT PATTERSON AFB OH 45433-7750
1	AFRL MLSS R THOMSON 2179 12TH ST RM 122 WRIGHT PATTERSON AFB OH 45433-7718
2	AFRL F ABRAMS J BROWN BLDG 653 2977 P ST STE 6 WRIGHT PATTERSON AFB OH 45433-7739
1	WATERWAYS EXPERIMENT D SCOTT 3909 HALLS FERRY RD SC C VICKSBURG MS 39180
5	DIRECTOR LLNL R CHRISTENSEN S DETERESA F MAGNESS M FINGER MS 313 M MURPHY L 282 PO BOX 808 LIVERMORE CA 94550

NO. OF COPIES	ORGANIZATION
1	AFRL MLS OL L COULTER 7278 4TH ST BLDG 100 BAY D HILL AFB UT 84056-5205
1	OSD JOINT CCD TEST FORCE OSD JCCD R WILLIAMS 3909 HALLS FERRY RD VICKSBURG MS 29180-6199
1	DEFENSE NUCLEAR AGENCY INNOVATIVE CONCEPTS DIV 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
3	DARPA M VANFOSSEN S WAX L CHRISTODOULOU 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
2	FAA TECH CENTER P SHYPRYKEVICH AAR 431 ATLANTIC CITY NJ 08405
2	SERDP PROGRAM OFC PM P2 C PELLERIN B SMITH 901 N STUART ST STE 303 ARLINGTON VA 22203
1	FAA MIL HDBK 17 CHAIR L ILCEWICZ 1601 LIND AVE SW ANM 115N RESTON VA 98055
1	US DEPT OF ENERGY OFC OF ENVIRONMENTAL MANAGEMENT P RITZCOVAN 19901 GERMANTOWN RD GERMANTOWN MD 20874-1928

NO. OF COPIES	ORGANIZATION
1	DIRECTOR LLNL F ADDESSIO MS B216 PO BOX 1633 LOS ALAMOS NM 87545
1	OAK RIDGE NATIONAL LABORATORY R M DAVIS PO BOX 2008 OAK RIDGE TN 37831-6195
3	DIRECTOR SANDIA NATIONAL LABS APPLIED MECHANICS DEPT MS 9042 J HANDROCK Y R KAN J LAUFFER PO BOX 969 LIVERMORE CA 94551-0969
1	OAK RIDGE NATIONAL LABORATORY C EBERLE MS 8048 PO BOX 2008 OAK RIDGE TN 37831
1	OAK RIDGE NATIONAL LABORATORY C D WARREN MS 8039 PO BOX 2008 OAK RIDGE TN 37831
7	NIST R PARNAS J DUNKERS M VANLANDINGHAM MS 8621 J CHIN MS 8621 D HUNSTON MS 8543 J MARTIN MS 8621 D DUTHINH MS 8611 100 BUREAU DR GAITHERSBURG MD 20899
1	HYDROGEOLOGIC INC SERDP ESTCP SPT OFC S WALSH 1155 HERNDON PKWY STE 900 HERNDON VA 20170

NO. OF COPIES	ORGANIZATION
3	NASA LANGLEY RSCH CTR AMSRL VS W ELBER MS 266 F BARTLETT JR MS 266 G FARLEY MS 266 HAMPTON VA 23681-0001
1	NASA LANGLEY RSCH CTR T GATES MS 188E HAMPTON VA 23661-3400
1	FHWA E MUNLEY 6300 GEORGETOWN PIKE MCLEAN VA 22101
4	CYTEC FIBERITE R DUNNE D KOHLI M GILLIO R MAYHEW 1300 REVOLUTION ST HAVRE DE GRACE MD 21078
1	USDOT FEDERAL RAILRD M FATEH RDV 31 WASHINGTON DC 20590
1	CENTRAL INTLLGNC AGNCY OTI WDAG GT W L WALTMAN PO BOX 1925 WASHINGTON DC 20505
1	MARINE CORPS INTLLGNC ACTVTY D KOSITZKE 3300 RUSSELL RD STE 250 QUANTICO VA 22134-5011
1	DIRECTOR NATIONAL GRND INTLLGNC CTR IANG TMT 220 SEVENTH ST NE CHARLOTTESVILLE VA 22902-5396
1	SIOUX MFG B KRIEL PO BOX 400 FT TOTTEN ND 58335

NO. OF COPIES	ORGANIZATION
1	DIRECTOR DEFENSE INTLLGNC AGNCY TA 5 K CRELLING WASHINGTON DC 20310
1	ADVANCED GLASS FIBER YARNS T COLLINS 281 SPRING RUN LANE STE A DOWNINGTON PA 19335
1	COMPOSITE MATERIALS INC D SHORTT 19105 63 AVE NE PO BOX 25 ARLINGTON WA 98223
1	JPS GLASS L CARTER PO BOX 260 SLATER RD SLATER SC 29683
1	COMPOSITE MATERIALS INC R HOLLAND 11 JEWEL CT ORINDA CA 94563
1	COMPOSITE MATERIALS INC C RILEY 14530 S ANSON AVE SANTA FE SPRINGS CA 90670
2	COMPOSIX D BLAKE L DIXON 120 O NEILL DR HEBRUN OH 43025
2	SIMULA J COLTMAN R HUYETT 10016 S 51ST ST PHOENIX AZ 85044
2	PROTECTION MATERIALS INC M MILLER F CRILLEY 14000 NW 58 CT MIAMI LAKES FL 33014

NO. OF COPIES	ORGANIZATION
3	FOSTER MILLER J J GASSNER M ROYLANCE W ZUKAS 195 BEAR HILL RD WALTHAM MA 02354-1196
1	ROM DEVELOPMENT CORP R O MEARA 136 SWINEBURNE ROW BRICK MARKET PLACE NEWPORT RI 02840
2	TEXTRON SYSTEMS T FOLTZ M TREASURE 201 LOWELL ST WILMINGTON MA 08870-2941
1	GLCC INC J RAY 103 TRADE ZONE DR STE 26C WEST COLUMBIA SC 29170
1	O GARA HESS & EISENHARDT M GILLESPIE 9113 LESAINT DR FAIRFIELD OH 45014
2	MILLIKEN RSCH CORP H KUHN M MACLEOD PO BOX 1926 SPARTANBURG SC 29303
1	CONNEAUGHT INDUSTRIES INC J SANTOS PO BOX 1425 COVENTRY RI 02816
2	BATTELLE NATICK OPNS J CONNORS B HALPIN 209 W CENTRAL ST STE 302 NATICK MA 01760
1	ARMTEC DEFENSE PRODUCTS S DYER 85 901 AVE 53 PO BOX 848 COACHELLA CA 92236

NO. OF COPIES	ORGANIZATION
3	PACIFIC NORTHWEST LAB M SMITH G VAN ARSDALE R SHIPPELL PO BOX 999 RICHLAND WA 99352
8	ALLIANT TECHSYSTEMS INC C CANDLAND MN11 2830 C AAKHUS MN11 2830 B SEE MN11 2439 N VLAHAKUS MN11 2145 R DOHRN MN11 2830 S HAGLUND MN11 2439 M HISSONG MN11 2830 D KAMDAR MN11 2830 600 SECOND ST NE HOPKINS MN 55343-8367
2	AMOCO PERFORMANCE PRODUCTS M MICHNO JR J BANISAUKAS 4500 MCGINNIS FERRY RD ALPHARETTA GA 30202-3944
1	SAIC M PALMER 1410 SPRING HILL RD STE 400 MS SH4 5 MCLEAN VA 22102
1	SAIC G CHRYSSOMALLIS 3800 W 80TH ST STE 1090 BLOOMINGTON MN 55431
1	AAI CORPORATION T G STASTNY PO BOX 126 HUNT VALLEY MD 21030-0126
1	APPLIED COMPOSITES W GRISCH 333 NORTH SIXTH ST ST CHARLES IL 60174
1	CUSTOM ANALYTICAL ENG SYS INC A ALEXANDER 13000 TENSOR LANE NE FLINTSTONE MD 21530

NO. OF COPIES	ORGANIZATION
3	ALLIANT TECHSYSTEMS INC J CONDON E LYNAM J GERHARD WV01 16 STATE RT 956 PO BOX 210 ROCKET CENTER WV 26726-0210
1	OFC DEPUTY UNDER SEC DEFNS JAMES THOMPSON 1745 JEFFERSON DAVIS HWY CRYSTAL SQ 4 STE 501 ARLINGTON VA 22202
1	PROJECTILE TECHNOLOGY INC 515 GILES ST HAVRE DE GRACE MD 21078
5	AEROJET GEN CORP D PILLASCH T COULTER C FLYNN D RUBAREZUL M GREINER 1100 WEST HOLLYVALE ST AZUSA CA 91702-0296
3	HEXCEL INC R BOE PO BOX 18748 SALT LAKE CITY UT 84118
1	HERCULES INC HERCULES PLAZA WILMINGTON DE 19894
1	BRIGS COMPANY J BACKOFEN 2668 PETERBOROUGH ST HERNDON VA 22071-2443
1	ZERNOW TECHNICAL SERVICES L ZERNOW 425 W BONITA AVE STE 208 SAN DIMAS CA 91773
1	OLIN CORPORATION L WHITMORE 10101 NINTH ST NORTH ST PETERSBURG FL 33702

NO. OF COPIES	ORGANIZATION
2	OLIN CORPORATION FLINCHBAUGH DIV E STEINER B STEWART PO BOX 127 RED LION PA 17356
1	GKN AEROSPACE D OLDS 15 STERLING DR WALLINGFORD CT 06492
5	SIKORSKY AIRCRAFT G JACARUSO T CARSTENSAN B KAY S GARBO MS S330A J ADELMANN 6900 MAIN ST PO BOX 9729 STRATFORD CT 06497-9729
1	PRATT & WHITNEY C WATSON 400 MAIN ST MS 114 37 EAST HARTFORD CT 06108
1	AEROSPACE CORP G HAWKINS M4 945 2350 E EL SEGUNDO BLVD EL SEGUNDO CA 90245
2	CYTEC FIBERITE M LIN W WEB 1440 N KRAEMER BLVD ANAHEIM CA 92806
1	HEXCEL T BITZER 11711 DUBLIN BLVD DUBLIN CA 94568
1	BOEING R BOHLMANN PO BOX 516 MC 5021322 ST LOUIS MO 63166-0516
1	UDLP G THOMAS PO BOX 58123 SANTA CLARA CA 95052

NO. OF COPIES	ORGANIZATION
2	UDLP R BARRETT MAIL DROP M53 V HORVATICH MAIL DROP M53 328 W BROKAW RD SANTA CLARA CA 95052-0359
3	UDLP GROUND SYSTEMS DIVISION M PEDRAZZI MAIL DROP N09 A LEE MAIL DROP N11 M MACLEAN MAIL DROP N06 1205 COLEMAN AVE SANTA CLARA CA 95052
4	UDLP R BRYNSVOLD P JANKE MS 170 4800 EAST RIVER RD MINNEAPOLIS MN 55421-1498
1	UDLP D MARTIN PO BOX 359 SANTA CLARA CA 95052
2	BOEING DFNSE & SPACE GP W HAMMOND S 4X55 J RUSSELL S 4X55 PO BOX 3707 SEATTLE WA 98124-2207
2	BOEING ROTORCRAFT P MINGURT P HANDEL 800 B PUTNAM BLVD WALLINGFORD PA 19086
1	BOEING DOUGLAS PRODUCTS DIV L J HART SMITH 3855 LAKEWOOD BLVD D800 0019 LONG BEACH CA 90846-0001
1	LOCKHEED MARTIN S REEVE 8650 COBB DR D 73 62 MZ 0648 MARIETTA GA 30063-0648

NO. OF COPIES	ORGANIZATION
1	LOCKHEED MARTIN SKUNK WORKS D FORTNEY 1011 LOCKHEED WAY PALMDALE CA 93599-2502
1	LOCKHEED MARTIN R FIELDS 1195 IRWIN CT WINTER SPRINGS FL 32708
1	MATERIALS SCIENCES CORP B W ROSEN 500 OFC CENTER DR STE 250 FT WASHINGTON PA 19034
1	NORTHRUP GRUMMAN CORP ELECTRONIC SENSORS & SYSTEMS DIV E SCHOCH MS V 16 1745A W NURSERY RD LINTHICUM MD 21090
2	NORTHROP GRUMMAN ENVIRONMENTAL PROGRAMS R OSTERMAN A YEN 8900 E WASHINGTON BLVD PICO RIVERA CA 90660
1	GDLS DIVISION D BARTLE PO BOX 1901 WARREN MI 48090
2	GDLS D REES M PASIK PO BOX 2074 WARREN MI 48090-2074
1	GDLS MUSKEGON OPERATIONS W SOMMERS JR 76 GETTY ST MUSKEGON MI 49442

NO. OF COPIES	ORGANIZATION
1	GENERAL DYNAMICS AMPHIBIOUS SYS SURVIVABILITY LEAD G WALKER 991 ANNAPOLIS WAY WOODBRIDGE VA 22191
6	INST FOR ADVANCED TECH H FAIR I MCNAB P SULLIVAN S BLESS W REINECKE C PERSAD 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
2	CIVIL ENGR RSCH FOUNDATION PRESIDENT H BERNSTEIN R BELLE 1015 15TH ST NW STE 600 WASHINGTON DC 20005
1	ARROW TECH ASSO 1233 SHELBURNE RD STE D8 SOUTH BURLINGTON VT 05403-7700
1	R EICHELBERGER CONSULTANT 409 W CATHERINE ST BEL AIR MD 21014-3613
1	UCLA MANE DEPT ENGR IV H T HAHN LOS ANGELES CA 90024-1597
2	UNIV OF DAYTON RESEARCH INST R Y KIM A K ROY 300 COLLEGE PARK AVE DAYTON OH 45469-0168
1	MIT P LAGACE 77 MASS AVE CAMBRIDGE MA 01887

NO. OF COPIES	ORGANIZATION
1	IIT RESEARCH CENTER D ROSE 201 MILL ST ROME NY 13440-6916
1	GA TECH RSCH INST GA INST OF TCHNLGY P FRIEDERICH ATLANTA GA 30392
1	MICHIGAN ST UNIV MSM DEPT R AVERILL 3515 EB EAST LANSING MI 48824-1226
1	UNIV OF KENTUCKY L PENN 763 ANDERSON HALL LEXINGTON KY 40506-0046
1	UNIV OF WYOMING D ADAMS PO BOX 3295 LARAMIE WY 82071
2	PENN STATE UNIV R MCNITT C BAKIS 212 EARTH ENGR SCIENCES BLDG UNIVERSITY PARK PA 16802
1	PENN STATE UNIV R S ENGEL 245 HAMMOND BLDG UNIVERSITY PARK PA 16801
1	PURDUE UNIV SCHOOL OF AERO & ASTRO C T SUN W LAFAYETTE IN 47907-1282
1	STANFORD UNIV DEPT OF AERONAUTICS & AEROBALLISTICS S TSAI DURANT BLDG STANFORD CA 94305

NO. OF COPIES	ORGANIZATION
1	UNIV OF DAYTON J M WHITNEY COLLEGE PARK AVE DAYTON OH 45469-0240
7	UNIV OF DELAWARE CTR FOR COMPOSITE MTRLS J GILLESPIE M SANTARE G PALMESE S YARLAGADDA S ADVANI D HEIDER D KUKICH 201 SPENCER LABORATORY NEWARK DE 19716
1	DEPT OF MATERIALS SCIENCE & ENGINEERING UNIVERSITY OF ILLINOIS AT URBANA CHAMPAIGN J ECONOMY 1304 WEST GREEN ST 115B URBANA IL 61801
1	NORTH CAROLINA STATE UNIV CIVIL ENGINEERING DEPT W RASDORF PO BOX 7908 RALEIGH NC 27696-7908
1	UNIV OF MARYLAND DEPT OF AEROSPACE ENGNRNG A J VIZZINI COLLEGE PARK MD 20742
3	UNIV OF TEXAS AT AUSTIN CTR FOR ELECTROMECHANICS J PRICE A WALLS J KITZMILLER 10100 BURNET RD AUSTIN TX 78758-4497
3	VA POLYTECHNICAL INST & STATE UNIV DEPT OF ESM M W HYER K REIFSNIDER R JONES BLACKSBURG VA 24061-0219

NO. OF COPIES	ORGANIZATION
1	DREXEL UNIV A S D WANG 32ND & CHESTNUT ST PHILADELPHIA PA 19104
1	SOUTHWEST RSCH INST ENGR & MATL SCIENCES DIV J RIEGEL 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510
	ABERDEEN PROVING GROUND
1	US ARMY MATERIEL SYSTEMS ANALYSIS ACTIVITY P DIETZ 392 HOPKINS RD AMXSY TD APG MD 21005-5071
1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP AP L APG MD 21005-5066
105	DIR USARL AMSRL CI AMSRL CI H W STUREK AMSRL CI S A MARK AMSRL CS IO FI M ADAMSON AMSRL SL B J SMITH AMSRL SL BA AMSRL SL BL D BELY R HENRY AMSRL SL BG AMSRL SL I AMSRL WM E SCHMIDT AMSRL WM B A HORST AMSRL WM BA F BRANDON

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND (CONT)

AMSRL WM BC
P PLOSTINS
D LYON
J NEWILL
S WILKERSON
A ZIELINSKI
AMSRL WM BD
B FORCH
R FIFER
R PESCE RODRIGUEZ
B RICE
AMSRL WM BE
C LEVERITT
D KOOKER
AMSRL WM BR
C SHOEMAKER
J BORNSTEIN
AMSRL WM M
D VIECHNICKI
G HAGNAUER
J MCCAULEY
B TANNER
AMSRL WM MA
R SHUFORD
P TOUCHET
N BECK TAN
AMSRL WM MA
D FLANAGAN
L GHIORSE
D HARRIS
S MCKNIGHT
P MOY
P PATTERSON
G RODRIGUEZ
A TEETS
R YIN
AMSRL WM MB
B FINK
J BENDER
T BOGETTI
R BOSSOLI
L BURTON
K BOYD
S CORNELISON
P DEHMER
R DOOLEY
W DRYSDALE
G GAZONAS
S GHIORSE
D GRANVILLE

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND (CONT)

AMSRL WM MB
D HOPKINS
C HOPPEL
D HENRY
R KASTE
M KLUSEWITZ
M LEADORE
R LIEB
E RIGAS
J SANDS
D SPAGNUOLO
W SPURGEON
J TZENG
E WETZEL
A FRYDMAN
AMRSL WM MC
J BEATTY
E CHIN
J MONTGOMERY
A WERECZCAK
J LASALVIA
J WELLS
AMSRL WM MD
W ROY
S WALSH
AMSRL WM T
B BURNS
AMSRL WM TA
W GILLICH
T HAVEL
J RUNYEON
M BURKINS
E HORWATH
B GOOCH
W BRUCHEY
AMSRL WM TC
R COATES
AMSRL WM TD
A DAS GUPTA
T HADUCH
T MOYNIHAN
F GREGORY
A RAJENDRAN
M RAFTENBERG
M BOTELER
T WEERASOORIYA
D DANDEKAR
A DIETRICH

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND (CONT)

AMSRL WM TE
A NIILER
J POWELL
AMSRL SS SD
H WALLACE
AMSRL SS SE R
R CHASE
AMSRL SS SE DS
R REYZER
R ATKINSON
AMSRL SE L
R WEINRAUB
J DESMOND
D WOODBURY

NO. OF COPIES	ORGANIZATION
1	LTD R MARTIN MERL TAMWORTH RD HERTFORD SG13 7DG UK
1	SMC SCOTLAND P W LAY DERA ROSYTH ROSYTH ROYAL DOCKYARD DUNFERMLINE FIFE KY 11 2XR UK
1	CIVIL AVIATION ADMINSTRATION T GOTTESMAN PO BOX 8 BEN GURION INTERNL AIRPORT LOD 70150 ISRAEL
1	AEROSPATIALE S ANDRE A BTE CC RTE MD132 316 ROUTE DE BAYONNE TOULOUSE 31060 FRANCE
3	DRA FORT HALSTEAD P N JONES M HINTON SEVEN OAKS KENT TN 147BP UK
1	DEFENSE RESEARCH ESTAB VALCARTIER F LESAGE COURCELETTE QUEBEC COA IRO CANADA
1	SWISS FEDERAL ARMAMENTS WKS W LANZ ALLMENDSTRASSE 86 3602 THUN SWITZERLAND
1	DYNAMEC RESEARCH AB AKE PERSSON BOX 201 SE 151 23 SODERTALJE SWEDEN

NO. OF COPIES	ORGANIZATION
1	ISRAEL INST OF TECHNOLOGY S BODNER FACULTY OF MECHANICAL ENGR HAIFA 3200 ISRAEL
1	DSTO MATERIALS RESEARCH LAB NAVAL PLATFORM VULNERABILITY SHIP STRUCTURES & MTRLS DIV N BURMAN PO BOX 50 ASCOT VALE VICTORIA AUSTRALIA 3032
1	ECOLE ROYAL MILITAIRE E CELENS AVE DE LA RENAISSANCE 30 1040 BRUXELLE BELGIQUE
1	DEF RES ESTABLISHMENT VALCARTIER A DUPUIS 2459 BOULEVARD PIE XI NORTH VALCARTIER QUEBEC CANADA PO BOX 8800 COURCELETTE GOA IRO QUEBEC CANADA
1	INSTITUT FRANCO ALLEMAND DE RECHERCHES DE SAINT LOUIS DE M GIRAUD 5 RUE DU GENERAL CASSAGNOU BOITE POSTALE 34 F 68301 SAINT LOUIS CEDEX FRANCE
1.	ECOLE POLYTECH J MANSON DMX LTC CH 1015 LAUSANNE SWITZERLAND

NO. OF COPIES	ORGANIZATION
1	TNO PRINS MAURITS LABORATORY R IJSSELSTEIN LANGE KLEIWEG 137 PO BOX 45 2280 AA RIJSWIJK THE NETHERLANDS
2	FOA NATL DEFENSE RESEARCH ESTAB DIR DEPT OF WEAPONS & PROTECTION B JANZON R HOLMLIN S 172 90 STOCKHOLM SWEDEN
2	DEFENSE TECH & PROC AGENCY GROUND I CREWTHER GENERAL HERZOG HAUS 3602 THUN SWITZERLAND
1	MINISTRY OF DEFENCE RAFAEL ARMAMENT DEVELOPMENT AUTH M MAYSELESS PO BOX 2250 HAIFA 31021 ISRAEL
1	TNO DEFENSE RESEARCH I H PASMAN POSTBUS 6006 2600 JA DELFT THE NETHERLANDS
1	B HIRSCH TACHKEMONY ST 6 NETAMUA 42611 ISRAEL
1	DEUTSCHE AEROSPACE AG DYNAMICS SYSTEMS M HELD PO BOX 1340 D 86523 SCHROBENHAUSEN GERMANY

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2001	Final, October 1998 - September 1999

4. TITLE AND SUBTITLE
Effects of Processing Conditions on Vacuum Assisted Resin Transfer Molding Process (VARTM)

5. FUNDING NUMBERS
COMP04STO

6. AUTHOR(S)
Elias J. Rigas, Thomas J. Mulkern, Shawn M. Walsh, and Steven P. Nguyen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-MB
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2480

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The continued growth of vacuum-based processes has warranted the development of both models and experimental studies designed to capture the unique aspects associated with this manufacturing technique. To that end, this report summarizes an initial set of experiments that characterize both the process and the resulting mechanical properties of components fabricated under a variety of process conditions. Specifically, resin flow studies are presented in part to demonstrate, the relative influence of key parameters on the flow front developed during impregnation. The effect of the distribution medium, which is used in a commercial version of VARTM known as Seeman's Composite Resin Infusion Molding Process (SCRIMP), is explicitly characterized. In addition, the variation of part thickness is also examined, and potential mechanisms responsible for these variations are presented. A battery of mechanical tests designed to correlate the effect of various processing conditions are also presented. A major finding is that thickness variation can be significant and, to some degree, random; also, precompaction of the preform significantly influences the amount of consolidation pressure needed during impregnation. Dimensional variations due to gradients in the pressure distribution of the vacuum affect permeability (and hence resin flow), as well as dimensional tolerances in manufactured parts.

14. SUBJECT TERMS
composite, resin, VARTM, processing, epoxy, fiberglass

15. NUMBER OF PAGES
44

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2480 (Rigas) Date of Report May 2001

2. Date Report Received ____________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ____________________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ____________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ____________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ____________________

CURRENT ADDRESS

Organization

Name E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

OFFICIAL BUSINESS

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY MAIL

FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL WM MB
ABERDEEN PROVING GROUND MD 21005-5069